Geotechnical Engineering for Transportation Infrastructure, Barends et al. (eds) © 1999 Balkema, Rotterdam, ISBN 90 5809 047 7

Embankment design for high speed trains on soft soils
Conception de remblais sur sols meubles pour les chemins de fer à grande vitesse

R.F. Woldringh
Projectorganization HSL-South, Utrecht, Netherlands,
DHV Environment and Infrastructure, Amersfoort, Netherlands

B.M. New
Associate, Geotechnical Consulting Group, London, UK

Keywords: high speed trains, embankments, dynamics, critical velocities, soft soils

ABSTRACT: In the Netherlands the Projectorganization HSL-South is involved in the construction of the high-speed link between Amsterdam and Brussels. Embankments overlying very soft soils are being considered with high train velocities, short construction time and very strict requirements on residual settlements being important factors in the design of the works. Given these requirements it was thought that conventional railway embankments would not be appropriate and the No-Recess research program was initiated. No-Recess stands for New Options for Rapid and Easy Construction of Embankments on Soft Soils. The design process and field trials are proving successful in demonstrating the application of recently developed geotechnical techniques and in testing new design methods that predict the dynamic performance (in terms of the ‘critical velocity’) of new embankments and for upgrading existing railways across soft soils.

RÉSUMÉ: Aux Pays-Bas, l’organisation du projet HSL-Sud participe à la construction d’une liaison à grande vitesse entre Amsterdam et Bruxelles. La conception des travaux est caractérisée par trois facteurs importants: la prise en compte de remblais recouvrant des sols très meubles dans le cadre de vitesses importantes de circulation des trains, une courte période de construction et des contraintes très strictes en ce qui concerne les tassements résiduels. Ces contraintes rendent inappropriés les remblais conventionnels, aussi un programme de recherche No-Recess (New Options for Rapid and Easy Construction of Embankment on Soft Soils) centré sur la définition de "nouvelles options pour la construction rapide et facile de remblais sur sols meubles" a été lancé. Le processus de conception et les essais sur le terrain se sont révélés fructueux pour la démonstration de l’application des techniques géotechniques récemment mises au point, pour l’expérimentation de nouvelles méthodes de conception capables de prévoir la performance dynamique (en termes de "vitesse critique") des nouveaux remblais, ainsi que l’expérimentation de méthodes de réhabilitation des chemins de fer existants traversant des sols meubles.

1 INTRODUCTION

The design speed of the proposed High Speed Link - South (HSL-S) in the Netherlands is 300 km/h (approx. 80 m/s) and the designers have studied the feasibility of using conventional embankments (wick drains and pre-loading) to cross the extremely soft soils present on some parts of the route. Important aspects that govern the design of the rail link are the relatively short construction time available and the strict requirements on residual settlements after construction. Further, a very important consideration for the design of the HSL-S is to evaluate the dynamic effects of a high-speed train on a low track bed because there is little experience of this problem in Holland. This question had been previously investigated during the design of the Channel Tunnel Rail Link across the Rainham Marshes in the UK.

According to Krylov (1994) one should take into account that "..... high speed trains could pose a similar problem to that presented by supersonic jets... . ....The large increase in ground vibration level results from the effect of a moving source approaching the "sound barrier", with regard to the velocity of Rayleigh surface waves propagating through the ground. The velocities of such waves in soft sandy soils may be very low (90-130 m/s)......". As the velocity of Rayleigh surface wave velocity in some soft soils in the Netherlands can be as low as 29 - 47 m/s, which is considerably lower than the railway’s proposed design speed, the matter clearly required investigation.

The main objective of the No-Recess trials is to test the suitability of various embankment construction techniques for a railway demanding very low long-term deformations. Whilst low settlement might suggest high stiffness and high stiffness implies suitability for high speed trains it is possible that a low settlement embankment could have an unsatisfactory dynamic performance. Therefore it was essential to consider the dynamic performance of the embankments and it is hoped that the data gained during the trials will enable the theoretical/empirical design methods developed to be refined and validated.

2 DESIGN CONSIDERATIONS / BACKGROUND

2.1 *Critical train velocities*

The Projectorganization of HSL-S felt the need to gather more information on the topic of high-speed trains on soft soils. In 1996 this organization invited geotechnical railway experts from five different European countries to collaborate on this topic. The meeting came to the following conclusion: The velocity of a high-speed train can approach or exceed the characteristic wave velocity of the dynamic system comprising, the underlying soft ground, the trackbed/embankment, and the moving load. As the train's velocity approaches some ‘critical velocity’ large deformations can occur (De Nie 1948, Fryba 1972). These motions could be dangerous for the train and the integrity of the structure, and potentially costly in terms of track maintenance. It is therefore vital to design embankments which provide a dynamic stiffness that will limit track displacements to acceptable levels.

The problem is sometimes referred to as the ‘undulation’, ‘bow wave’ or ‘critical velocity’ effect and is of importance when designing a new high-speed railway or when specifying geotechnical measures to up-grade an existing track for higher operating speeds.

Kenney (1954) gives some insight into the parameters that seem to be of importance to the ‘critical velocity’ v_{cr}.

$$v_{cr} = \sqrt[4]{\frac{4kEI}{\rho^2}} \tag{1}$$

where k = spring constant per unit length of beam; E = modulus of elasticity of beam; I = moment of inertia of beam; ρ = mass per unit length of beam. Kenney discusses a point load moving with constant velocity over an Euler-Bernoulli beam on a visco-elastic Winkler medium. In Kenney's analytical solution the embankment sub-soil system has to be simplified as a single beam supported by linear springs. Other methods are required to deal with changes in load magnitude and complexity of distribution because, for instance, the system may be non-linear.

2.2 *Design practice*

At present a robust link between theoretical analyses and practical embankment design does not exist (Kempfert et al (1992), Woldringh (1997), NS-RIB (1997a)) and structural solutions are usually employed in the construction of high-speed railways. These solutions provide track-beds with high stiffness and therefore the critical velocity is higher than the operating speed and this effectively removes the problem. Construction often take the form of track-beds supported on piled concrete foundations or low viaducts which, although usually expensive, provide a relatively well understood and risk free option.

Other solutions also involve the provision of high stiffness track support. For instance, it has been proposed by Rehfeld (1994) to build embankments with a good quality of fill (sand) down to a level of 5 m below the rail level and that this will cope with undesirable dynamic effects. In areas with extremely soft soils this solution could be unfavorable if only short construction time is available in combination with the demand of small residual settlements in the service period.

Hillig (1996) concludes that the influence of high train speeds is reduced, relative to track in ballast, if ballastless track (Feste Fahrbahn) systems are utilized. In these German systems the rails are supported by a continuous concrete slab. This is in accordance with the observations of De Nie (1948, 1949a, b). In the following section we shall elaborate on the observations of De Nie. In the Fast-Train-Link (Schnellfahrstrecke) Hannover-Berlin the German railways applied a piled embankment system using a loading platform of geotextiles on top of the piles. This system for the Fast-Train-Link was chosen for reasons of economy because removal of the soft soils (thickness of the compressible layers < 10 m) seemed to be more expensive.

Recent advances in geotechnologies, such as soil mixing and foundations using geotextiles, provide alternative solutions that may offer both good long-term deformation and dynamic performance with significant savings in construction costs.

2.3 *Field observations*

Measurements of rail deflections as a function of the train speed that indicate a dynamic amplification of rail deflections have been reported by De Nie (1948, 1949a, b), Fortin (1982), Sunaga et al (1990). The following authors report that considerable dynamic sub-structure phenomena can occur due to high (train) speed loading in a combination with certain (poor) geotechnical circumstances: Kempfert & Vogel (1992), Rehfeld (1994), Hillig (1996).

It is very interesting to note that the Dutch railway engineer De Nie was involved in the measurements of rail deflections performed during 1938-1940 on the track from Oudewater to Gouda. The measurements were carried out because the track needed a lot of maintenance and because "undulation"/bow-waves were detected in the track. The tests were performed using, for those days, conventional trains with speeds of 120 km/h (33 m/s). One can imagine that when the track was originally constructed in 1855 the design of the embankments did not consider the effect of high-speed trains. In a (probably) unpublished manuscript by De Nie (undated, approx. 1949b) that was traced in the old archives of the Dutch railways he states that rail deflections (undulation/bow-wave) are:

- a function of axle load
- a function of the thickness of the embankment fill
- a function of the elastic properties of the sub-soil and the damping in the system
- a function of the train speed
- both upward and downward (during the train passages sequential significant uplift and a downward deflection of the rail were observed)

De Nie discusses that at certain speeds "resonance" phenomena can cause rail deflections that are far larger than the static values. He also calculated that "resonance" would occur if a passenger train configuration traveled at a speed of 270 km/h and if a freight train configuration approached the speed of 217 km/h. De Nie reports that if the undulation/bow-wave/resonance phenomenon occurs it will involve excessive maintenance of the ballast and that speed reductions of the trains could be necessary.

The rail deflections reported by De Nie (1948, 1949a), at a train speed of 120 km/h, in the track and before the concrete slab was applied were 8-15 mm (peak-to-peak-values: uplift 2 mm, downward movement 6 mm, resp. uplift 4 mm, downward 11 mm). After the construction of the concrete slab the values of the peak-to-peak rail deflections were approx. 1.5 mm (no uplift of the rail above the unloaded rail level was recorded). At present the critical velocity of the original sub-structure system at the test location is not known.

The solution to deal with the relatively large rail deflections was the application of an approximately 0.5 m thick continuous concrete slab beneath the ballast. Test runs with trains showed that the rail deflections were reduced to 10% of the deflections without the concrete slab: a satisfactory result (De Nie (1948, 1949b)).

Because of the present relevance of his early observations (1938) and conclusions (1948) De Nie must be congratulated for considerable foresight and engineering skills.

Measurements of vertical deflections due to trains traveling at speeds up to 180 km/h over an embankment constructed on soft ground at Stilton Fen in the UK (1993) have shown displacements that increase very significantly with increasing speed. Figure 1 shows the data obtained at Stilton Fen as part of background investigations for the UK Channel Tunnel Rail Link and is presented here by kind permission of Union Railways Ltd. The displacements shown were measured on the ballast and represent peak-to-peak motions. The static deflection was estimated at 5 mm. The embankment was believed to comprise of ballast and ash to a depth of about 2.6m and a thin layer of silty sand and gravel which overlies peat and very soft silty clay.

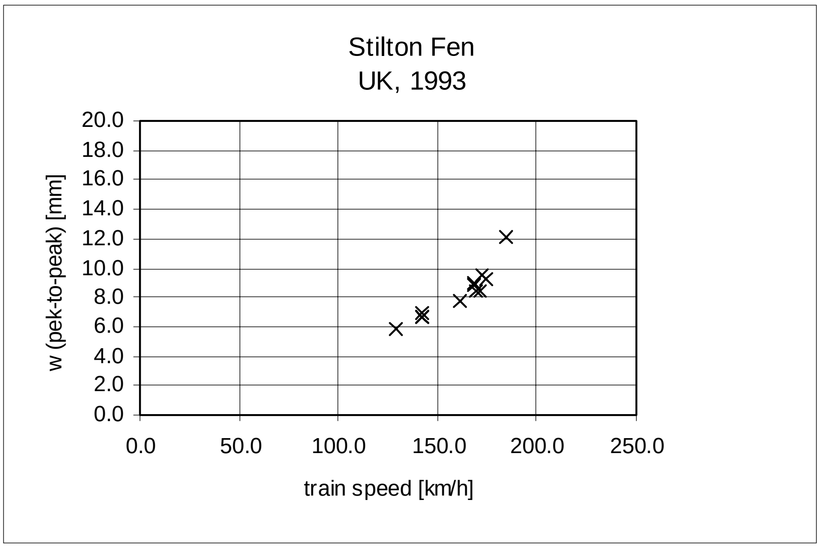

Figure 1. Peak-to-peak displacements, Stilton Fen (UK)

The Swedish newspaper Göteborg Posten (1997) reports on 24 June 1997 that the authorities ordered a speed reduction of the Swedish X2000 high speed train on the line Göteborg-Malmö. "The train would travel faster than the soil". Because of large observed deformations the speed of the train was reduced from 180 km/h to 160 km/h. According to SJ (1997) Reslust magazine of the Swedish railways we understand that the specific X2000 line was in operation since 9 June 1997. After this the Swedish Rail administration performed a further research program in this high speed rail link. Madshus (1998) and Adolfsson et al (1999) report on the test results, Figure 2.

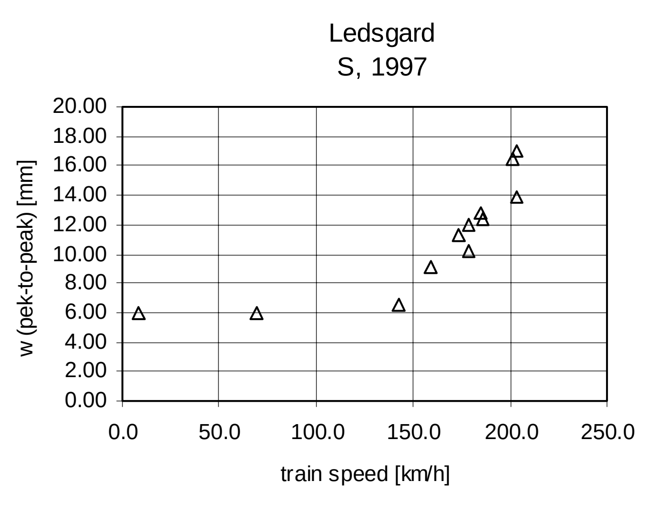

Figure 2. Peak-to-peak displacements, Ledsgard (S)

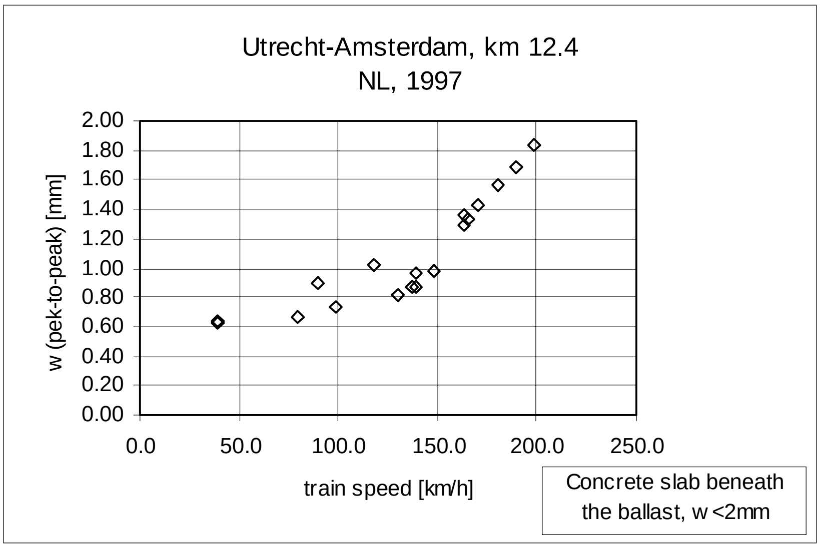

Figure 3. Peak-to-peak displacements Amsterdam-Utrecht, (NL)

In September 1997 the Dutch railways (NS-RIB; 1997a) published a press release concerning the tests with a French TGV on the existing track between Amsterdam and Utrecht. The embankments consist of 2m of sand fill over 6m soft clay and peat layers. The press release stated that experts from Germany, Great Britain, France, Switzerland and the Netherlands are convinced that rail deflections depend on the axle load and the train velocity. Planning to upgrade train velocities to speeds of 160 km/h and higher should involve an investigation. The investigation has been performed and has been reported to NS-Railinfrabeheer (Dutch Rail Administration) and the Projectorganizaton HSL-S. A significant amount of the measurements on the Swedish and Dutch tracks were accomplished during the same weekend: 3-4 and 5 October 1997. During the tests there was an on-site exchange of information. The Dutch tests were performed with a French TGV (Thalys) during June-October 1997. The test results achieved at km 12.4 on the line Amsterdam-Utrecht are presented in Figure 3 with permission of NS Railinfrabeheer.

3 DYNAMIC ASPECTS OF THE NO-RECESS RESEARCH

3.1 *General*

At the No-Recess test site 5 embankments have been constructed at full scale (each 80-120m long, sections 1-5m high). The 5 embankments have the codes HW1 up to HW5. HW stands for Hoeksche Waard, the name of the polder where test site is located. The test embankment HW1 is a conventional test embankment (sand fill, wick-drains and pre-loading). The embankments HW1, 2, 3 and 4 are embankments that will be subjected to a research program in order to determine the dynamic performance of these embankments.

All test embankments have a 5m high section and a 1m high section: The latter section will be dynamically tested. In these proceedings Van Duijvenbode et al (1999) gives further detail regarding the foundation of the test embankments. HW5 will not be subjected to dynamic tests because the construction is such that it is obvious that the dynamic performance is adequate.

3.2 *Preliminary design review*

Following the preliminary design of the No-Recess embankments an assessment of their likely relative dynamic characteristics was made and the designs were then revised to optimize the embankments both in terms of construction cost and overall performance.

In predicting the dynamic performance of the trial embankments a variety of theoretical models were considered and the likelihood of their successful application evaluated. All the models depended on knowledge of the embankments mass, it’s stiffness (modulus and moment of inertia), damping characteristics, and the modulus of the sub-grade reaction. Of these only the mass is likely to be well known and the other properties are difficult to reliably define. Sensitivity analyses indicated that any predictions based only on theoretical methods would have an unacceptable degree of uncertainty (for final design purposes).

In response to this problem a hybrid theoretical/empirical technique was developed which uses field data to calibrate the results from calculations related to a moving load on a beam on an elastic foundation. The model requires input in regard of the train type and considers a variety of assumptions in respect of the physical properties of the embankment/foundation structure. For the trial embankments it was not necessary to allow for any track structure. However where a track is present, and is found to significantly modify the "beam" model, this should be considered as part of the overall design of the system. This is discussed further below.

By considering a predicted ‘critical velocity’ as a measure of dynamic performance for any embankment the need to know the damping properties of the system is largely removed. The method does not permit the prediction of dynamic amplification factors but this is not of significance at present because most embankment designs will seek to ensure that the design speed of the trains will be less than about 60% of the critical velocity. At this level it appears that the amplification factor will not usually be significant (see Conclusions below).

By using the method to compare the known performance of the reference embankments with the various test embankments it is also possible to substantially mitigate difficulties in choosing the most appropriate model to define the modulus of sub-grade reaction (or the Winkler spring constant). This is because the test (and most actual) embankments have generally similar physical dimensions to the reference embankments.

For the reasons given above a holistic model for foundation/embankment/track design does not need to predict the changes in dynamic deflection waveforms which are associated with trains approaching any critical velocity because the system will be designed to avoid that possibility. Where, exceptionally, train speeds do approach a critical velocity the likely increased cost of maintenance, impact of increased track-side vibration and safety considerations may require remedial measures.

3.3 *Comparative Measures of Dynamic Performance*

Given that the 'critical velocities' for the reference embankments were estimated from field measurements the 'equivalent velocities' for the trial embankments are as shown in Table 1. The predicted values will be reviewed in the light of the final construction detail and actual physical properties of the embankment materials and their foundations.

Table 1. Critical velocities of system embankment-sub soil.

Embankment	Code	Critical velocity km/h
Reference (example)	Case A	206
Anhydrite-cement mixed columns,	HW2	440
FMI 'walls',	HW3	500
Sand filled geotextile columns,	HW4	360

Note that the predicted critical velocities for the principal test embankments are well above the design speed of the proposed railway.

The design review for the trial embankments indicated the potential advantages, in theory at least, of the continuous support provided to the embankment by the FMI wall (HW3) foundation over those using piles.

Even with the conservative design assumption that this form of construction only increases the sub-grade reaction modulus the method yielded the trial embankment with the highest critical velocity/dynamic stiffness. However because of the continuous nature of the linear support provided by the 'walls' it seems likely that they will contribute significantly to the stiffness of the assumed overlying beam as well as providing the sub-grade reaction. This dramatically changes the assumptions used in the models because we now must consider a deep composite beam, comprising the sand working layer and the FMI walls, which is founded at depth on a material with a high modulus of sub-grade reaction. (In this case the sands beneath the peat/alluvium). This change in assumption significantly increases the predicted dynamic stiffness of the embankment/foundation system. Because of the non-linear nature of the support provided by piled designs they cannot exhibit this apparently desirable feature.

Any piled or low viaduct solution (without a sufficient block stabilization overlying the piles) for a railway crossing soft ground necessarily presents a series of 'bridges' between stiffer foundation points. This may give rise to cyclic deflections as the axle/bogie loads move along the embankment and this is, in principle, less desirable than the constant impedance presented by a linear support system.

It is intended to evaluate the dynamic performance of the trial embankments using the DyStaFiT machine as a vibration source (Neidhart, 1998), Figure 4. During these tests vibration measurements will be made by geophone arrays already put in place. By analyzing the data at a range of frequencies it is hoped to obtain a good estimate of the dynamic response of the embankments. However it must be appreciated that because of the relatively short lengths of trial embankment available the dynamic performance cannot be directly measured in respect of a moving load and the link with the response under the fixed oscillating load (the DyStaFiT plate) must be made theoretically.

Figure 4. The DyStaFiT machine

4 CONCLUSIONS

The No-Recess trials are presenting a valuable opportunity to develop and test dynamic performance prediction methods on a variety of embankment structures whose construction and residual settlement characteristics are known in considerable detail. The results will be used to validate the method used during the design process and may lead to a relatively robust method for the economic design of embankments with dynamic properties fitted to the specific operational requirements of a new high-speed railway.

Further, a validated design model of this kind may be expected to find application in specifying and evaluating the geotechnical and other options that may be applied to upgrade foundations/embankments when operating speeds are required to increase on existing railways.

Purely theoretical design methods are severely hampered by difficulties in the determination of the dynamic physical properties of the embankment and it's foundation. The application of the hybrid empirical/theoretical model appears to present a practical solution to a problem which seems likely to become of increasing significance in the future. The model would benefit greatly from a database of measurements of dynamic deflections on embankments caused by test trains similar to those obtained at Stilton Fen, Amsterdam-Utrecht and Ledsgard. Such measurements would be particularly valuable for a range of construction types and embankment geometries.

Field measurements where the dynamic deflection magnification curve can be established beyond the critical velocity would be most useful as this would enable the damping of the system to be determined and the model developed further. This would need to be very carefully controlled because of the danger of derailment and may not be possible with safety.

Present indications (De Nie (1948, 1949a, b), data from Stilton Fen measurements, NS-RIB (1997b) and Madshus (1998)) are that dynamic deflections at the critical velocity can be at least two or three times the static deflection (Figure 5). This could be subject to wider variation because the dynamic deflection is a function of damping whereas the static is not and the variation in the damping properties of railway embankments is not well known at this time.

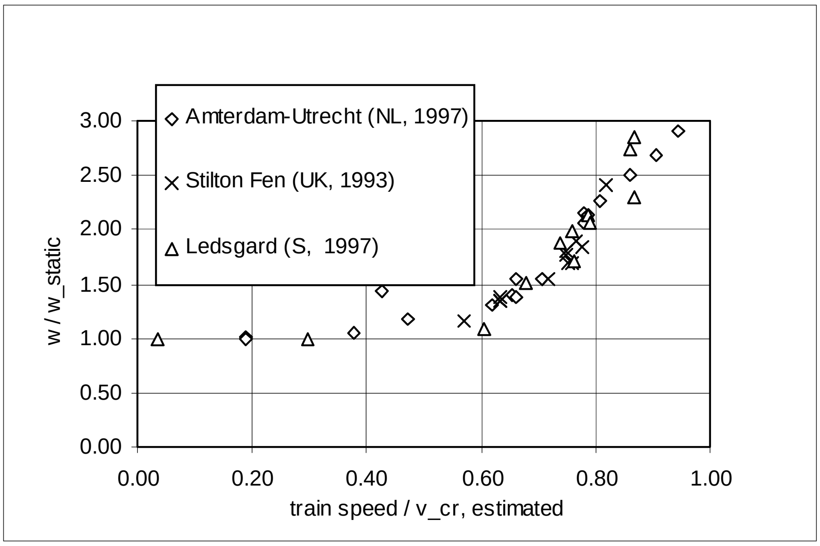

Figure 5. Scaled deflections (peak-to-peak) versus scaled train speed (dynamic amplification)

Figure 5 shows the rather remarkable similarity between the measurements taken in the UK, the Netherlands and Sweden when scaled in respect of static deflection and estimated critical velocity. This is very encouraging as it suggests a consistency in the physical properties across the three embankments investigated. This bodes well for the application of the design model used for the trial embankments to actual railway design.

If the foundation/embankment/track design for high-speed trains is approached as a holistic process (not usually done at present) which seeks to minimize residual and dynamic track deflections, trackside vibration and maintenance costs, then the following form of construction would appear worthy of serious consideration. *A wall type linear foundation beneath a granular embankment (probably with geotextile reinforcement) with a continuous form of concrete slab rail support.* This form of construction might be expected to provide a good dynamic performance at high speeds (high critical velocity) with minimized ground vibration because of the absence of foundation/embankment or track stiffness variations (i.e. no foundation or sleeper crossing frequencies). There may be significant cost savings over conventional concrete piled slab or low viaduct solutions. These techniques may also have environmental benefits in that the removal of ‘unsuitable’ and excavated soils may be greatly reduced.

5 ACKNOWLEDGEMENTS

The Authors are grateful to W. Korf, director of the Projectorganization HSL-South who made the No-Recess research possible. We would like to thank J.G. Baardman, NS-Railinfrabeheer for the permission to publish the data achieved during the tests performed in the line Amsterdam-Utrecht. We are very grateful to Union Railways Ltd for permission to publish the data from Stilton Fen.

REFERENCES

Adolfsson, K, & Andréasson, B. & Bengtsson, P.-E. & Zackrisson, P. 1999. High Speed Train X2000 on soft organic clay - measurements in Sweden. *Proceedings XIIth ECSMGE, Amsterdam, June 1999*: Rotterdam: Balkema.

De Nie, F.C. 1948. Undulation of railway embankments on soft sub-soil during passing of trains. *Proceedings of the 2-nd Conf. on Soil Mech. and Found. Engineering 1948, Vol. II*: pages 8-12

De Nie, F.C. 1949a. Verbetering van de Spoorbaan Oudewater-Gouda. *Spoor- en Tramwegen, 22e jaar, Nr.14, 14 juli 1949*: pages 209-212 and *Nr.15, 28 juli 1949*:pages 227-230 (Dutch)

De Nie, F.C. undated, approx. 1949b. De verbetering van spoorbanen op slappe grond. *Archives N.V. Nederlandse Spoorwegen*. Probably unpublished manuscript approx. 1949: Utrecht: Projectorganisatie HSL-Zuid Infra (Dutch).

Fortin, J.P. 1982 La déformée dynamique de la voie ferrée. *Revue Générale des Chemins de Fer, Février 1982, 101e année*: pages 93-102.

Fryba, L. 1972. Vibration of solids and structures under moving loads, ch.13:Groningen: Noordhoof

Göteborg Posten, 1997. X2000 tvingas sakta ned. *Göteborg Posten 24 June 1997*. Göteborg (Swedish)

Hillig, J. 1996. Geotechnische Anforderungen an den Eisenbahnunterbau. *Eisenbahningenieur 47, Marz 1996*: pages 24-31.

Kempfert, H.G. & Vogel, W. 1992. Grundsatzfragen des Erd- und Grundbaus für Hochgeschwindigkeitsstrecken, *AET Archiv für Eisenbahntechnik, 44, Ingenieursbauwerke de Neubaustrecken der Deutsche Bundesbahn, 1992*: pages 11-38.

Kenney, J.T. jr. 1954, Steady-State Vibrations of Beam on Elastic Foundation for Moving Load. *Journal of Applied Mechanics, December 1954*

Krylov, V.V. 1994. Ground vibrations generated by superfast trains. *Noise & Vibration worldwide, June 1994, Vol.25, No.6*: pages 7-9.

Madshus, C. & Kaynia, A.M. 1998. High Speed Railway Lines on Soft Ground: Dynamic Behaviour at Critical train Speed, *Paper at the 6th International Workshop on Railway Noise, November 1998*, France

Neidhart, Th. & Watzlaw , W. 1998. Überprüfung der dynamischen Untergrundstabilität und Optimierung von Bodenverbesserungsmaßnahmen, *Proceedings Baugrundtagung 1998* , Stuttgart.

NS-RIB, 1997a. Persbericht. *Praktijkproef met hoge treinsnelheid tussen Amsterdam en Utrecht, 26 september 1997*: Utrecht: NS Railinfrabeheer (Dutch).

NS-RIB, 1997b. Samenvatting en analyse metingen HSL, juni, september, oktober 1997. *TNO-rapport 97-CON-R1522, by P.C. van Staalduinen & G.P.C. van Oosterhout*: Utrecht: NS -Railinfrabeheer (Dutch).

Rehfeld, E. 1994. Untergrundbeschaffenheit. *Eisenbahningenieur 46, Nr.4, April 1995 (Vortrag anlässlich de Fachtachtung des VDEI "Bau von Hochleistungsstrecken" am 14 Oktober 1994 in Berlin)*: pages 258-264.

Reslust, 1997. X2000 nyheter, *Reslust, Nummer 2, Sommaren 1997*: page 25. Stockholm: Reslustmagasinet är utgivet av SJ Persontrafikdivision. (Swedish)

Sunaga, M. & Sekine, E, & Ito, T. 1990. Vibration Behaviours of Roadbed on Soft Grounds under Train Load. *Quar. Rep. of the Railway Technical Research Institute, Vol. 31, No. 1, February 1990*: pages 29-35. Japan.

Van Duijvenbode , J.D. & Woldringh, R.F. 1999. No-Recess test site Hoeksche Waard (Netherlands). *Proceedings XIIth ECSMGE, Amsterdam, June 1999*: Rotterdam: Balkema.

Woldringh, R.F. 1997. Notes on low embankments for high-speed lines on compressible subsoil. *PAO Course "High Speed Track", 11 June 1997*: Delft